

Development of Satellite Mill and Trial Rolling of Profiled Metal Strip

Y. Saito, T. Watanabe, and H. Utsunomiya

A new type of compact continuous mill called the "Satellite mill" has been developed to produce profiled metal strip from flat strip. This mill consists of one large-diameter driven roll (central roll) and five smaller rolls (satellite rolls) arranged along the periphery of the central roll. A strip is continuously rolled at five gaps between the central roll and the satellite rolls. All rolls are driven at an equal roll peripheral speed to promote transverse metal flow or lateral spread. Guide shoes are provided between the adjacent satellite rolls and are supported with two adjacent satellite rolls. They prevent a strip from bulging or buckling. A test mill was constructed, and rolling experiments have been performed on the production of T-shaped or U-shaped profiled aluminum strip. The deformation-load characteristics were investigated and compared with those of conventional rolling. As a result, in the satellite mill rolling operation, elongation was suppressed. Lateral spread was enhanced, and the profile of the product cross section was significantly improved. Consequently, the new rolling process was found to be forming of profiled metal strip.

1. Introduction

RECENTLY, long narrow metal strip with a profiled cross section, the thickness of which varies stepwise across the width (Fig. 1), is widely used in the electronics industry as raw materials for lead frames or various terminals.[1,2] Such strips are mainly produced from flat strips by the V-mill rolling method: intermittent forging, in which a set of V-shaped shaping die and a flat roller are used.[2] However, the method is less productive because many motions of the roller are required. Consequently, from the viewpoint of productivity and yield efficiency, the most advantageous process appears to be the continuous rolling operation.[3] Nevertheless, in continuous rolling, it is difficult to produce a profiled strip free from buckling at a thin portion without numerous passes.

This study discusses a new compact mill that can produce profiled strip efficiently in one pass, or in several passes at most. This article outlines the newly developed rolling mill, called the satellite mill,[4] and deformation-load characteristics of the mill are described.

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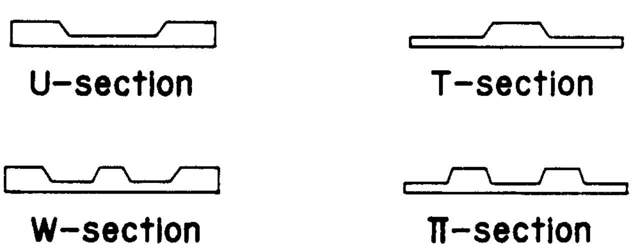
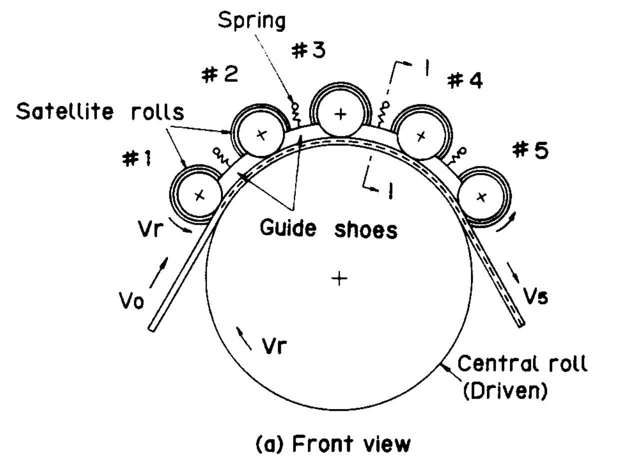


Fig. 1 Typical cross sections of profiled metal strip.



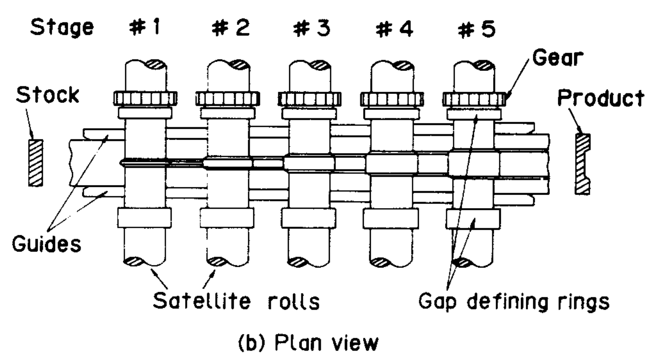


Fig. 2 Basic layout of rolls in the five-stage satellite mill rolling setup.

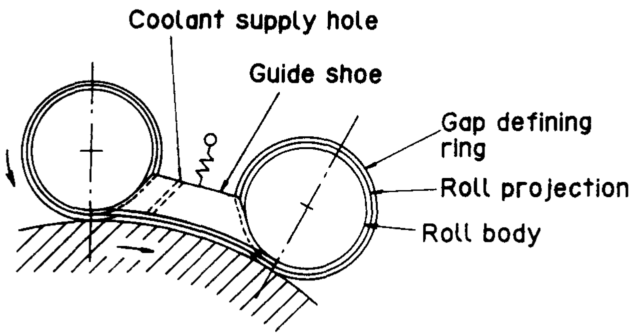


Fig. 3 Guide shoe supported by two adjacent satellite rolls.

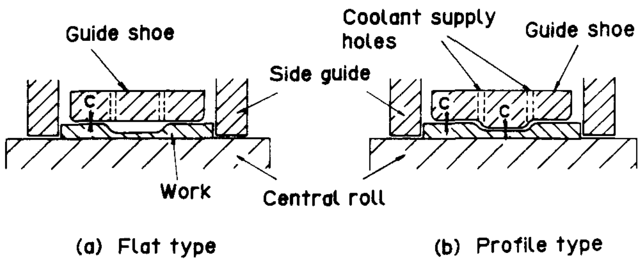


Fig. 4 Cross sections taken on line I-I of Fig. 2(a) showing two types of guide shoes.

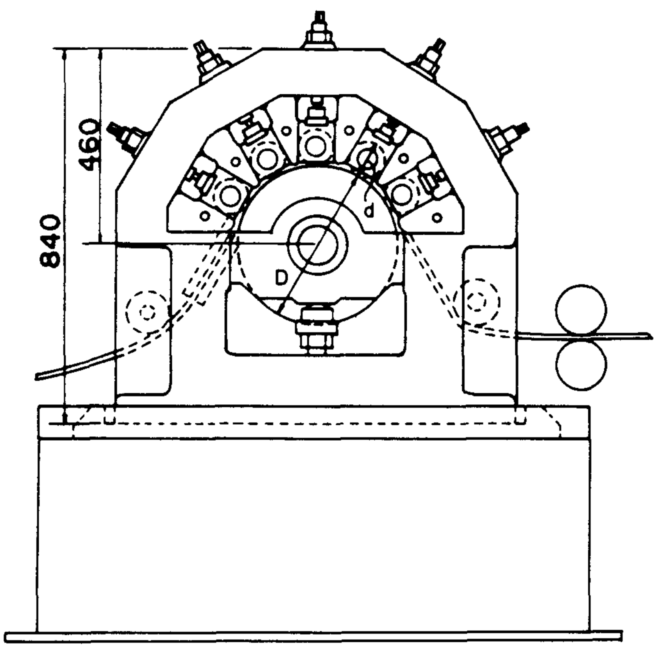


Fig. 5 Front view of prototype of five-stage satellite mill (D = 350 mm and d = 70 mm).

2. Rolling Method

Figure 2 shows the basic layout of rolls in the satellite mill. This setup consists of one central roll and several satellite rolls.

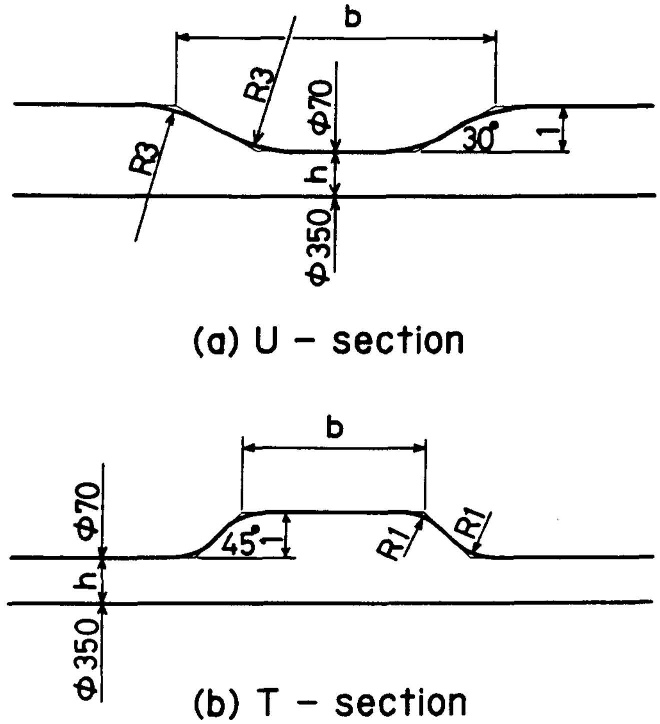


Fig. 6 Roll passes used in satellite mill rolling.

The diameter of the central roll is larger than its body length, and the diameters of satellite rolls are much smaller. Satellite rolls are arranged along the periphery of the central roll a set distance apart. A flat strip is rolled into a profiled strip by passing through the gaps between the central roll and satellite rolls continuously. Consequently, this arrangement of rolls constitutes a compact five-stand tandem mill. Each rolling position on the satellite mill is referred to as a "stage." Figure 2 depicts a five-stage satellite mill. In principle, each roll is driven independently. In this study, however, all satellite rolls were coupled to the central roll by gears so that they were driven at the same roll peripheral speed as the central roll. This type of satellite mill rolling is known as the caliber satellite roll method, in which caliber satellite rolls and a flat central roll are used. In the "caliber central roll method," flat satellite rolls and a caliber central roll are used. In this study, the caliber satellite roll method is discussed. Each satellite roll has projections that reduce the thickness of a certain portion of the width longitudinally. The widths of the projections increase with an increase in stage number.

Besides the central roll and the satellite rolls, guide shoes and side guides (Fig. 2 and 3) play important roles. Bulging of the strip is expected to occur between the satellite rolls because the strip is elongated and all peripheral roll speeds are the same. Also, steady-state rolling cannot be established. The guide shoes are expected not only to constrain the strip to contact with the central roll, but also to prevent buckling at a thin portion.

Figure 4 shows the two common types of guide shoes, *i.e.*, flat type (Fig. 4a) and profiled type (Fig. 4b). The flat type is used for the upstream stage where the groove of the strip is relatively narrow, and the profile type is used for the downstream

Table 1 Plastic Properties of Aluminum Strip (JIS-A1050P)

Temper grade	Proof stress, MPa	Tensile strength, MPa	Elongation, %	n-value ($0.03 < \bar{\varepsilon} < 1.45$)
O	37	76	47	0.23
H24	119	121	24	0.08

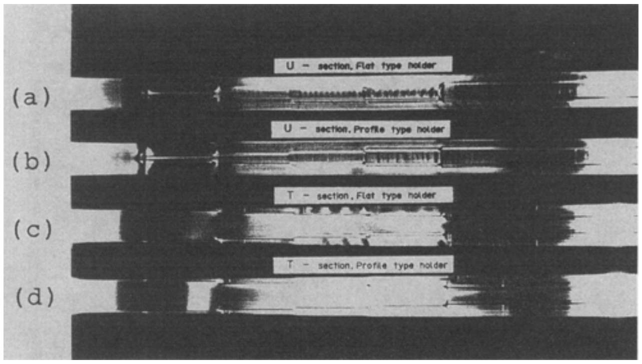


Fig. 7 Strip (A1050P-H24) under deformation in the five-stage satellite mill rolling operation showing effect of the type of guide shoe on buckling formation. **(a)** U-shaped profile with flat-type guide shoe. **(b)** U-shaped profile with profile-type guide shoe. **(c)** T-shaped profile with flat-type guide shoe. **(d)** T-shaped profile with profile-type guide shoe.

stage where the groove is so wide that buckling tends to occur at the thin portion. To prevent buckling, the clearance between the strip and the base of the guide shoe must be kept within a certain narrow range. This can be ensured by supporting the guide shoe with the two adjacent satellite rolls (Fig. 3). Thus, frictional forces develop between the guide shoe and the satellite rolls, as well as between the guide shoe and the workpiece. Therefore, the guide shoes, the rolls, and the workpiece must be lubricated adequately to decrease friction.

Furthermore, to obtain straight products, the pass center of each satellite roll must be in alignment, and the strip must be guided laterally by side guides, as shown in Fig. 2 and 4.

3. Experiment

3.1 *Equipment*

Figure 5 schematically represents the front view of the satellite mill constructed on an experimental basis. The diameter of the central roll (D) and the maximum diameter of the satellite rolls (d) are 350 and 70 mm, respectively. The body length of the rolls is 125 mm. The two adjacent satellite rolls are arranged at an angle of 30° on the central roll axis. The central roll is powered by a 1.5-kW motor through a variable-speed gearbox, giving a roll peripheral speed ranging from 25 to 92 mm/s. Load cells are equipped for continuous measurement of the roll separating force of all rolls. Furthermore, tubes that supply the lubricant to the rolls and the guide shoes and side guides are also provided .

Table 2 Typical Pass Schedule

Stage No.	b, mm U-shaped	b, mm T-shaped	h, mm
1	5	35	1.20
2	9	31	1.15
3	13	27	1.10
4	17	23	1.05
5	21	19	1.00

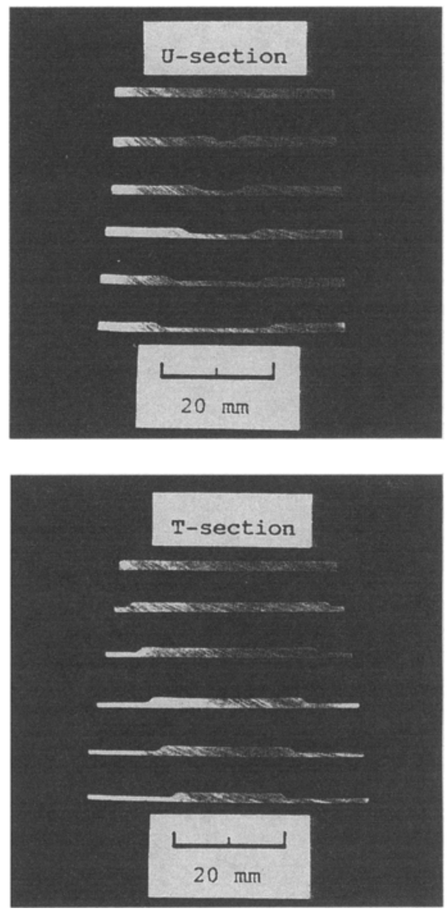


Fig. 8 Cross sections of strip before rolling and after passing each stage of the five-stage satellite mill. Material was A1050P-O.

3.2 *Roll Forms*

Two representative cross sections of the profiled metal strip, *i.e.*, U-shaped and T-shaped, were used for rolling experiments.

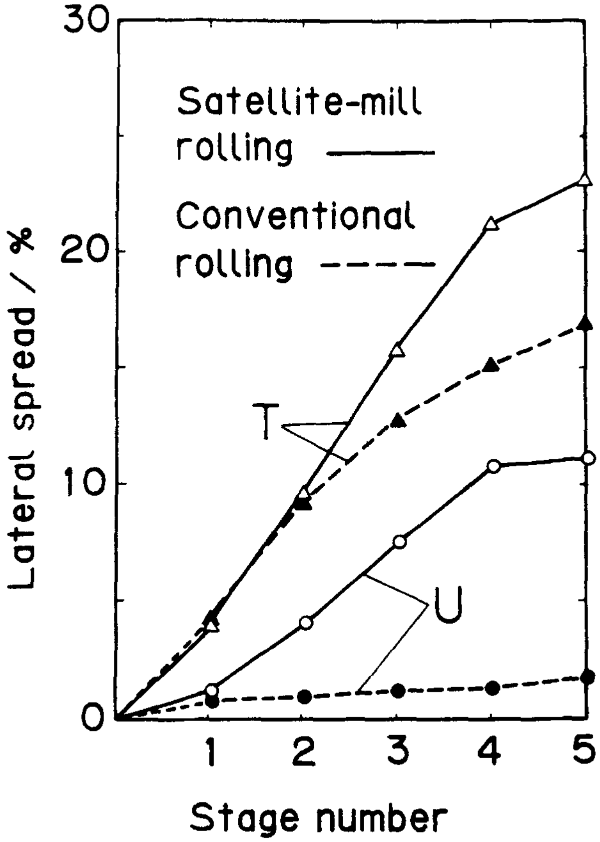


Fig. 9 Lateral spreading of strip during five-stage satellite mill rolling compared to conventional five-pass rolling. Material was A1050P-O.

The roll passes used in the experiments are shown in Fig. 6. Side inclination angles and corner radii of the roll passes were designed to accommodate the occurrence of surface defects.

3.3 *Workpiece*

The test material was a commercially pure aluminum strip in coil (JIS A1050P) 1.96 mm thick and 40 mm wide. It was subjected to either of the two standard heat treatments before testing, *i.e.*, fully annealed (temper grade O) and partially annealed (temper grade H24). The plastic properties of the test material are shown in Table 1. The work-hardening exponent, n, is defined by Eq 1, in which $\sigma_{0.2}$ is the 0.2% tensile proof stress of strip that has been cold rolled to an arbitrary reduction (r) in thickness.

$$\sigma_{0.2} = K\bar{\varepsilon}^n = K(2/\sqrt{3}\,|\ln(1-r)|)^n \qquad \text{(Eq 1)}$$

3.4 *Experimental Conditions*

The satellite mill rolling experiments were conducted under the following conditions. The pass schedule shown in Table 2 was applied for each section. Profile-type guide shoes were commonly used. The clearance between the base of the guide shoe and the workpiece was set to about 0.5 mm. Neither front tension nor back tension was applied to the strip both on the entering side and on the delivery side of the mill. The peripheral roll speed of all rolls was 25 mm/s, and a mineral oil-base rolling lubricant (IDEMITSU CU-50, kinematic viscosity at 313 K is 7.4 cm^2/s) was used.

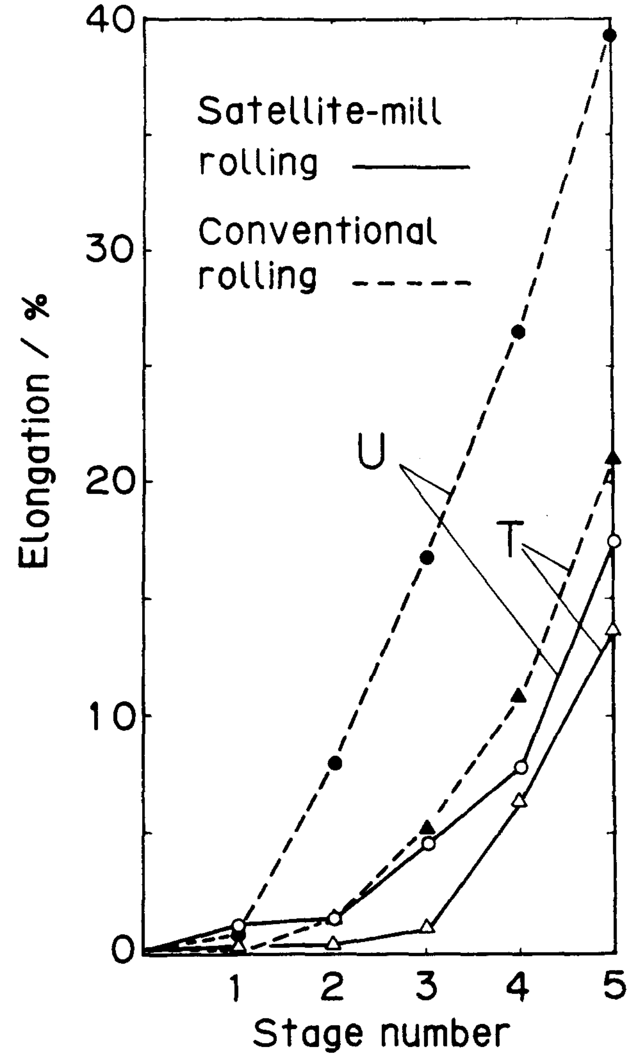


Fig. 10 Elongation of strip during five-stage satellite mill rolling compared to conventional five-pass rolling. Material was A1050P-O.

3.5 *Measurement*

After steady-state rolling was reached, the rolling operation was interrupted, and the partly rolled strip was pulled out of the mill by lifting up the satellite rolls. Then, dimensions, elongation, and slip of the strip were measured, and the shape (flatness) and surface quality were observed. Lateral spread and elongation of the ith stage (No. i) were defined as:

$$\text{Lateral spread} = (B_i/B_o) - 1 \qquad (i = 1,2,3,4,5) \qquad \text{(Eq 2)}$$

$$\text{Elongation} = (l_i/l_o) - 1 = \lambda_i - 1 \qquad (i = 1,2,3,4,5) \qquad \text{(Eq 3)}$$

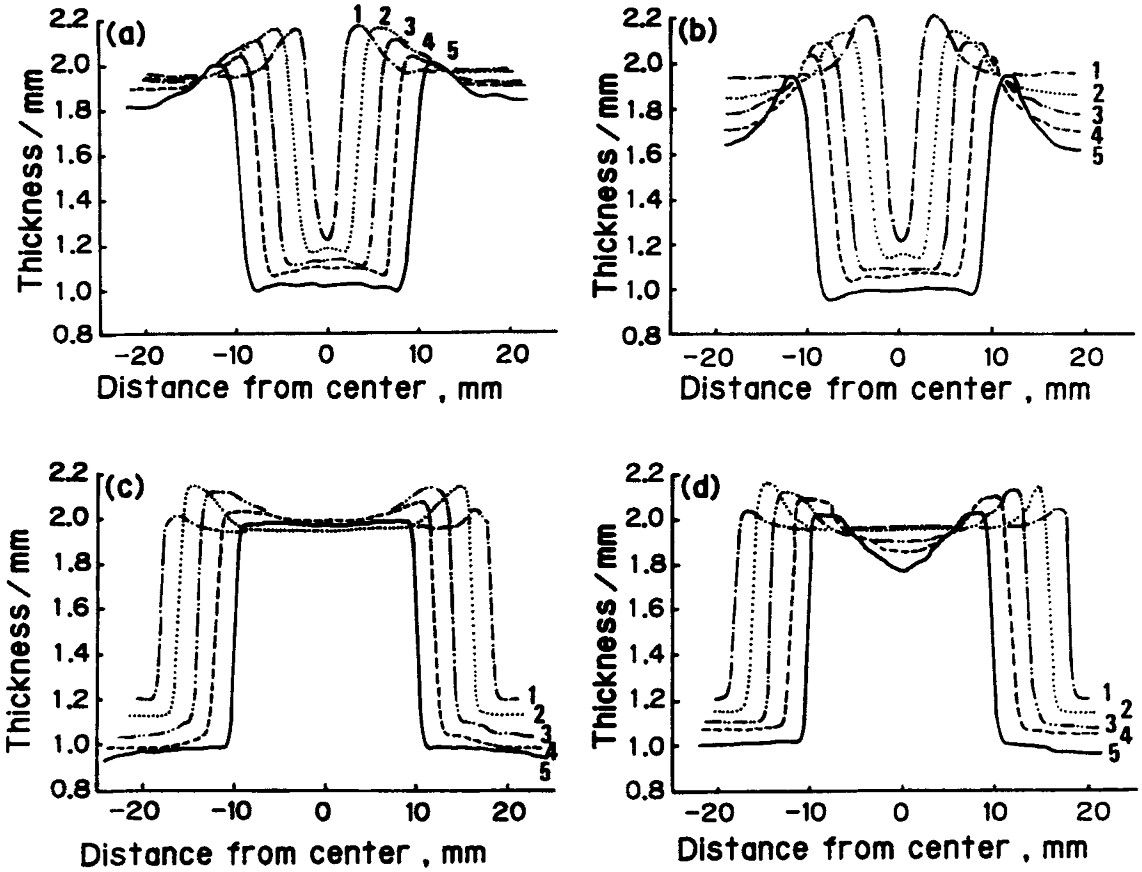


Fig. 11 Change in profile of strip during five-stage satellite mill rolling compared to conventional five-pass rolling. Material was A1050P-O. **(a)** U-shaped by satellite mill rolling. **(b)** U-shaped by conventional rolling. **(c)** T-shaped by satellite mill rolling. **(d)** T-shaped by conventional rolling.

where B_i is the width of the strip, and l_i is the longitudinal distance between a pair of reference lines on the strip surface between ith and $(i+1)$th stages, and B_o and l_o are their initial values before rolling, respectively. The forward slip coefficient of the strip was determined as follows by using a roll mark technique:

$$\text{Forward slip coefficient} = (V_i/V_r) = (L/\pi d)\ (\lambda_i/\lambda_5) \quad (i = 1,2,3,4,5) \qquad \text{(Eq 4)}$$

where V_i is the delivery speed of the strip from the ith stage, and L is the distance of the roll marks (transverse line scratched on the surface of the final satellite roll) left on the product. If the forward slip coefficient exceeds unity at a certain stage, then the stage is the neutral stage where the neutral point exists. In the other stages, the neutral point does not exist. For comparison purposes, a series of conventional two-high five-pass rolling experiments were also conducted under the same rolling conditions as those used for satellite mill rolling. For this purpose, only the third stage of the satellite mill was used, and the satellite rolls were exchanged according to the same pass schedule.

4. Results

4.1 *Appearance of Partly Rolled Sheet*

Figure 7 shows the typical appearance of strip being formed in a U-shape or T-shape during satellite mill rolling (straightened for observation convenience). This photograph clearly shows the effect of the guide shoes. When the flat shoes were used in all positions (a and c), buckling appeared both in the thin web of the U-shape and in the thin flanges of the T-shape after passing the third stage. However, the buckling of the T-shape disappeared at the final stage, whereas buckling of the U-shape remained as slight surface defects on the product. On the other hand, when the profile-type guide shoes were used (b and d), no buckling appeared in the T-shaped strip, and the buckling of the U-shaped strip was significantly reduced. In addition, in the rolling of the U-shaped strip, where the constraint by the side guides are indispensable contrary to the T-shape, the soft strip (grade O) is particularly difficult to guide laterally along the pass line.

The sequential changes in the profiles occurring during satellite mill rolling are shown in Fig. 8. In both cases, cross sections of the products fit to the shape of the roll pass, although in the thick portion the surface near the groove edges tends to

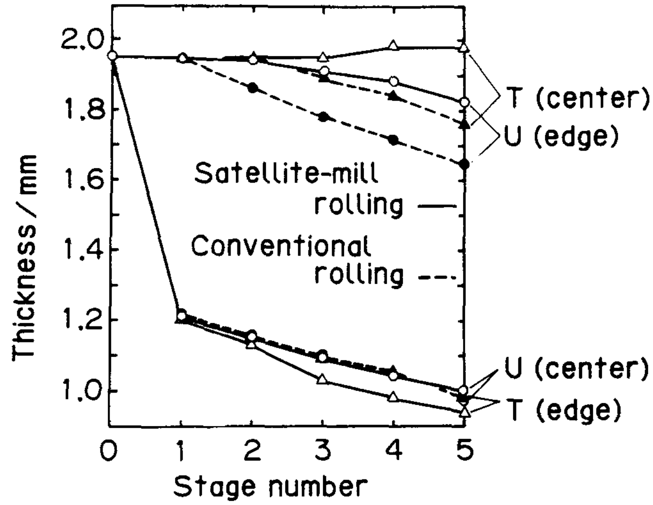


Fig. 12 Change in thickness of strip during five-stage satellite mill rolling compared to conventional five-pass rolling. Material was A1050P-O.

build up slightly and to sink in the portion distant from the groove edges. For instance, the thickness at the side edges of the U-shaped strip and the thickness at the center of the T-shaped strip are reduced.

4.2 *Lateral Spread, Elongation, and Forward Slip*

The variations in the lateral spread at each stage during satellite mill rolling and those at each pass of conventional rolling are compared in Fig. 9. Variations in elongations are similarly plotted in Fig. 10. In satellite mill rolling, the lateral spreads at the second, third, and fourth stages are much larger, and elongations at these stages are much smaller than those in the corresponding passes of the conventional rolling. This effect seems to be more pronounced in the U-shaped strip than in the T-shaped strip. From measurement of the forward slip coefficient, it was found that a neutral point exists in the fifth stage in the U-shaped strip and in the fourth stage in case of T-shaped strip.

4.3 *Profile of the Cross Section*

Sequential changes in the profile (thickness distribution across the width) during satellite mill rolling are shown in Fig. 11 in comparison with those during the corresponding conventional rolling. In Fig. 12, variations in the thickness of strip during rolling are plotted. Although in conventional rolling, significant excess reduction in thickness (sinking) occurs at both edges of the U-shaped strip and at the web of the T-shaped strip in satellite mill rolling, it does not occur (T-shaped strip) or decreases considerably (U-shaped strip). Consequently, in terms of the profile cross section, satellite mill rolled strip is superior to conventionally rolled strip.

4.4 *Roll Force*

In Fig. 13, the roll separating forces measured at each stage of the satellite mill are compared with those of the corresponding pass in conventional rolling. The roll force at the second, third, and fourth stages of the satellite mill is 1.5 to 2 times larger than those of the corresponding pass in the conventional rolling. Figure 13 indicates further that a larger roll force is needed in the rolling of the U-shaped strip than in the rolling of the T-shaped strip, especially at the first, second, and third stage. However, in the case of T-shaped strip, the stage loaded maximum roll force corresponds to the neutral stage, and in the case of U-shaped strip, that stage does not correspond to the neutral stage. The roll forces are also found to increase in comparison to conventional rolling at stages where elongation is suppressed and lateral spread is enhanced.

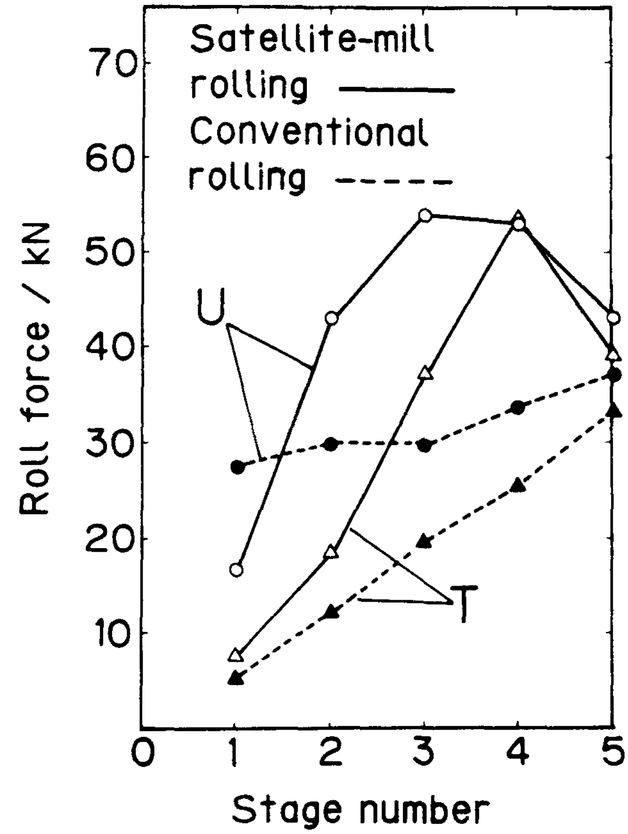


Fig. 13 Roll force at each stage of five-stage satellite mill rolling compared to conventional five-pass rolling. Material was A1050P-O.

5. Discussion

The foregoing experiments clearly show that satellite mill rolling is quite different from conventional continuous caliber rolling. In each stage of satellite mill rolling, particularly in the intermediate stages, elongation is significantly suppressed, lateral spreading is encouraged, and the roll force is correspondingly enhanced compared with conventional rolling.

These effects in satellite mill rolling can be explained consistently if it is assumed that a longitudinal compressive stress develops in the strip and grows toward its maximum value at a neutral point. This interstage compression is obviously attributed to the fact that all rolls are driven at an equal peripheral roll speed to prevent elongation of the strip. This stress assists the metal in the roll bite to flow transversely and enables the efficient forming of a profiled strip from a flat strip.

However, compression causes buckling in the thin portion. The buckling, or waviness, is likely to occur even without such compression because the local elongation at the thin portion tends to exceed the apparent elongation of the strip. Compression promotes the local compressive stress near the groove edges to reach a sufficient level for the thin groove to buckle more easily.

Both the buckling and the increase in the roll force accelerate wear of the guide shoes and rolls and increase the elastic deformation of the mill. These problems have been partly solved by the use of profile-type guide shoes with small clearance. However, further study is needed.

6. Conclusion

A new method of continuous rolling that uses a new type of compact mill (satellite mill) consisting of a central roll and five small satellite rolls arranged along the periphery of the central roll has been proposed. The test mill was constructed, and several rolling experiments were performed for trial production of U-shaped and T-shaped profiled strip from aluminum flat strip. In this rolling method, the transverse metal flow occurs more easily due to longitudinal compressive stress, and the profiles of product cross sections are improved significantly. It has been confirmed that profiled strip can be produced more efficiently by this method than by conventional rolling.

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